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The effect of 12-week long exercise intervention, and 2-weeks of detraining period on lower limbs strength parameters and postural stability in older adults: a linear mixed model analysis

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Abstract

Background Muscle strength and postural control are essential components for performing daily living activities, particularly in older adults, and can therefore serve as screening tools for assessing fall risk in this population.

Methods The aim of this quasi-experimental study was to evaluate the impact of a 12-week exercise intervention followed by a 2-week detraining period on lower limb strength and postural stability in older adults. The study involved 38 community-dwelling participants of Central European origin over 60 years of age. Participants underwent the measurements consisting of assessments of knee flexors and extensors strength (isokinetic dynamometer, 90° range of motion, 60°/s angular velocity, Humac Norm CSMI, Stoughton MA, USA), toe grip strength (toe grip dynamometer, Takei Scientific Instruments, Niigata, Japan), and postural stability (narrow stand, 30 s, Kistler, Switzerland). Testing was repeated three times during the study (pre-intervention, post-intervention, and post-detraining). Participants were separated into 3 groups according to the type of training: resistance training group ($n=13$), proprioceptive training group ($n=14$), and endurance training group ($n=11$). The intervention program lasted 12 weeks, two 60-min sessions per week. A linear mixed model (LMM) predicted a change in postural stability after the resistance, proprioceptive, and endurance exercise interventions were applied.

Results Results showed that knee extensor strength normalized to body mass significantly increased in the resistance training group post-intervention ($p=0.01$). Toe grip strength was significantly higher after the intervention in the endurance training group ($p=0.02$). A statistically significant increase in knee flexor strength was observed in the proprioceptive training group ($p=0.01$). The 2-weeks detraining period revealed no statistically significant loss in training gains. The LMM found different predictions of postural stability changes related to knee extensor strength after each type of training intervention. The final LMM model explains well the variability of the dependent variable $R^2 = 0.866$.

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Conclusions These results highlight the unique characteristics of specific exercise interventions in enhancing muscular strength and postural stability, which are critical for fall prevention among older adults.

Keywords Aged, Female, Male, Postural balance, Muscle strength, Resistance training, Falls prevention

Introduction

Population ageing and the increasing risk of falls with advanced age are the current challenges for health care systems [1–3] As falls might results in serious consequences such as fractures, disability, loss of mobility, and/or fear of falling resulting in a decreased quality of life [4], it is important to create effective fall prevention programs.

Exercise has been reported to be a cost-effective fall prevention program [5]. The risk factors of falls which can be improve by exercise consists of reduced muscle strength, impaired balance, and gait [6]. It has been previously demonstrated that gait, balance and strengthening exercises are moderately effective in improving balance in older adults immediately post-intervention [7]. However, other studies show that there is not enough evidence to determine the effect of walking or resistance training programs on the rate of falls [8]. Still, the previous literature agrees on the need to promote physical activity in older adults as no-intervention control groups were observed to have impaired balance compared to their exercising counterparts [9].

Recent research further supports the role of structured exercise interventions in improving functional capacity and reducing fall risks among older adults. A study evaluating a four-month balance training program found significant improvements in mobility and quality of life indicators such as physical function, balance, and walking endurance in elderly individuals. The study highlights that balance-specific exercises can reduce fall risk by up to 40% while also enhancing overall well-being in aging populations [10]. Another study examined the impact of self-myofascial release using a foam roller and found that it contributes to musculoskeletal improvements, such as increased flexibility and reduced lumbar lordosis, which are critical for maintaining postural stability [11]. These findings emphasize that multimodal exercise programs—including balance, strength, and flexibility training—are key to mitigating fall-related risks and maintaining independence in elderly individuals.

Postural control is a complex process integrating musculoskeletal, proprioceptive, vestibular, and visual systems to maintain the centre of mass within the base of support and it is essential for activities of daily living [12–14]. Melzer et al. [15] showed that postural stability in narrow base stance is a good screening tool for the risk of falls prediction in older adults. Study by Menant et al. shows that knee extensors strength is also a significant predictor of risk of falls and balance in older adults. Older adults with weak knee extensors were observed to have impaired balance and were more likely to fall in the following year [6]. Furthermore, the joint instability caused by the differences in the force reduction between agonist and antagonist muscles groups may exacerbate the muscle weakness and increase the risk of falls [16, 17]. Dynamic knee joint stability can be evaluated by conventional ratio, the ratio between concentric quadriceps and concentric hamstring ratio. Ratio below the reference value of 0.5 suggests affected knee join muscle balance and higher shearing forces of the joint increasing the risk of osteoarthritis development [18–20]. Previous studies show that exercise interventions can improve the hamstring/quadriceps ratio suggesting improved knee joint stability [21, 22]. Additionally, the toe flexor strength which correlates with knee extensors strength [23] and its decrease was observed to be associated with the risk of falls [24, 25].

This underscores the critical need for sustained exercise regimes to preserve the improvements in muscle balance and joint stability, which are otherwise susceptible to rapid decline during periods of detraining. Detraining, or interruption in training, results in the gradual loss of the training gains and the knowledge about detraining process may help the training professionals to better control and plan the training interruptions. In older adults, the interruptions in training are common, e.g., prolonged vacation, family commitments or reduced motivation to maintain regular trainings [26–29].

Postural control and muscle strength are critical components for performing daily activities and serve as vital indicators for fall-risk assessment in older adults. Previous studies reported promising exercise interventions [8], however; their heterogeneity in exercise types, intervention period, and reported benefits, suggest that comprehensive studies are necessary to develop standardized, effective fall prevention protocols for older adults. Therefore, our study aimed to comprehensively evaluate the impact of a 12-week long resistance, proprioceptive and endurance exercise intervention on lower limb strength parameters of knee joint and toe grip, and their subsequent influence on postural stability in these older adults. The resistance, proprioceptive, and endurance training were selected based on their ability to target key fall risk factors—muscle strength, balance control, and gait efficiency—each playing a crucial role in postural stability. This approach allows us to assess their individual effects and provide evidence-based recommendations for tailored exercise interventions in older adults. Furthermore, recognizing the limited research on the repercussions of detraining, we incorporated a subsequent 2-week detraining period to explore its effects on lower limb strength and postural stability. The used linear mixed model analysis elucidate the changes in postural stability following the various exercise interventions, offering insights into the most effective strategies for fall prevention in older adults.

Methods

Participants

In our quasi-experimental study, 44 community dwelling-participants aged over 60 years from Brno, the second-biggest city (396 101 inhabitants) in the Czech Republic and its surroundings were asked to participate. The recruitment period began on April 7, 2019, and ended on April 30, 2019.

Inclusion criteria consisted of [1] ≥60 years old, (2) living independently, (3) Passing the Montreal Cognitive Assessment (MoCA), (4) able to walk ≥10 m unaided, and (5) no neurological (e.g., Parkinson's, stroke) or oncological conditions. The exclusion criteria consisted of (1) severe musculoskeletal issues (e.g., osteoarthritis, recent fractures), (2) unstable cardiovascular disease, (3) need for mobility aids, and (4) engaged in structured lower limb training in the past six months.

After the initial screening, 38 participants fulfilled the criteria for participation in the study. All participants had given written informed consent before entering the study. The procedures performed in this study were anonymous and according to the Declaration of Helsinki, also approved by the Ethics Committee of the Faculty of Sport Studies of Masaryk University, Brno, Czech Republic (EKV-2018–088-R1). The participants were assigned to three intervention sub-cohorts by stratified randomization ensuring balance across key factors, including baseline fitness levels, age, and sex distribution.

The baseline characteristics of participants in each intervention group are shown in Table 1. No statistically significant difference in age, body height or body mass was observed between groups.

Study design

This study followed a quasi-experimental design. At the beginning of the study, participants completed Montreal Cognitive Assessment (MoCA) [30]. MoCA was validated as a highly sensitive tool for early detection of mild cognitive impairment (MCI). The total possible score is 30 points; a score of 26 or above is considered normal. All participants scored 26 or more points. Subsequently, they underwent a series of tests assessing their anthropometric characteristics, postural stability, knee flexors and extensors strength, and toe grip strength.

The testing was followed by one of the intervention scenarios (e.g., resistance training, proprioceptive training or endurance training). Same tests were performed after the end of the intervention period, and after a two-week detraining period. Participants were asked not to perform any intensive activity 48 h before the testing. Before the first testing, the participants attended two introduction sessions and an initial diagnosis for exercise intensity determination to prevent the risk of losing the participants during the intervention. The study design is shown in Fig. 1.

Table 1 Participants' characteristics

Intervention program	Gender (*n*)	Age (years)		Body height (cm)		Body mass (kg)		BMI		Waist/hip Ratio	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Resistance training	females ($n=8$)	70.75	3.67	159.59	6.91	84.38	9.66	33.18	3.57	0.88	0.06
	males ($n=5$)	65.80	1.72	175.70	8.28	89.46	17.98	29.07	6.04	0.95	0.05
Proprioceptive training	females ($n=7$)	70.71	4.59	161.46	3.27	75.50	10.21	28.96	3.84	0.89	0.06
	males ($n=7$)	70.00	5.29	171.74	2.99	87.15	9.56	29.59	3.59	1.00	0.05
Endurance training	females ($n=5$)	70.20	3.43	159.54	5.51	79.62	8.57	31.34	3.66	0.94	0.12
	males ($n=6$)	69.17	3.76	173.38	6.90	90.22	13.54	30.01	3.97	1.01	0.06

Fig. 1 Study design

Anthropometric characteristics
Anthropometric characteristics evaluated in this study were measured body mass and body height. Body mass was assessed in light indoor clothes and without shoes using InBody720 (Biospace, Korea), and height was measured using a calibrated stadiometer.

Postural stability
Postural stability was measured on Kistler force plates (Kistler, Switzerland) with eyes opened, and eyes closed. Participants were asked to stand as still as possible with a narrow stance (heels and big toes touching) for 30 s twice. The better performance was further analysed. From the Kistler software, centre of pressure (CoP) parameters was obtained. Studies have demonstrated that Kistler force plates are reliable and valid tools for assessing postural stability in older adults [31].

Lower limb strength measurement
Knee flexors and extensors strength was analysed using an isokinetic dynamometer Humac Norm CSMI (Stoughton MA, USA). The testing was performed using concentric mode with a 90° knee motion range and angular velocities of 60°/s. Six sub-maximal attempts with gradual strength-increasing expression intended to muscle warm-up were performed prior to the actual test. Knee extensors and flexors strength normalised to body mass and HQ ratio were further analysed. Isokinetic dynamometry is widely regarded as the gold standard for assessing muscle strength, providing objective and reproducible measures [32].

Toe grip was measured twice for each foot when sitting, both hips and knees were flexed 90° using toe grip dynamometer (Takei Scientific Instruments, Niigata, Japan). The higher value of toe grip strength normalised to body mass was used. Studies show that toe grip dynamometers have high reproducibility and strong intra- and interrater reliability [31].

Intervention programs
Participants were included into one of three types of 12-week intervention training programs, each of them was performed twice per week (60 min/session), with a total of 24 sessions. The programs followed the FITT principle (Frequency, Intensity, Time, and Type) to ensure a structured and progressive approach (Table 2). There were no events or injuries that prevented the completion of the study during the study. The minimum adherence to training interventions was 75% in all participants.

Table 2 Characteristics of intervention programs

	Resistance training group	Proprioceptive training group	Endurance training group
Frequency	twice per week, 12 weeks	twice per week, 12 weeks	twice per week, 12 weeks
Intensity	70–80% of 1RM	NA	Moderate (12–13 on the Borg scale)
Time	60 min/session	60 min/session	60 min/session
Type	Resistance training	Proprioceptive training	Endurance training

Resistance training

Resistance training consisted of 3 sets per exercise per muscle group, 8–12 repetitions, intensity 70–80% of 1RM, exercise selection 8–10 different exercises, modality free-weight or machine-based exercises. Each session included a 10-min warm-up, ended with a 5-min cooldown period. A specially trained coach carefully supervised each exercise. The design of the protocol was based on previous research in older adults [33, 34].

Proprioceptive training

Proprioceptive training consisted of specific proprioceptive exercises that were conducted in static and dynamic positions with the bosu and gym ball as unstable training tools that were designed to program proprioceptive training. The training was progressively structured in 3 phases. Initial phase: weeks 1–5; intermediate phase: weeks 5–8; and advanced phase: weeks 8–12. The individual phases are described in more detail in the study conducted by Martínez-Amat [35]. The exercise sessions were carefully supervised by a fitness specialist and at the end of each session a 10-min cooldown period of stretching and relaxation exercises was performed.

Endurance training

Before this intervention, the participants were taught the Nordic walking technique according to guidelines by a certified Nordic walking trainer. The endurance intervention included standard Nordic walking exercises in the surrounding forest. Each session ended with a 5-min cooldown period of slow walking and stretching. During the training, participants were instructed to walk as fast as it was comfortable. Training intensity was based on the subjective perception of exertion. The intensity of the training was based on subjective perception of exertion and was controlled using the Borg scale.

The training was set at a moderate intensity of load, which has been shown to have significant improvements in muscle strength and postural control [36].

Detraining period

After finishing the post-intervention testing, all participants were oriented not to perform any physical exercise during the next 2 weeks. After this period the participants again underwent tests to assess the detraining effects. The participants assured us that they neither attended other physical activity programs nor performed physical exercise during this detraining period. Thus, the detraining of the current study consists of 2 weeks without performing any physical exercise.

Statistical analysis

To analyse the differences between pre-training, post-training, and post-detraining testing, the ANOVA test was used together with Scheffe post hoc tests, chosen for their suitability in comparing multiple time points while controlling for Type I error. The level of statistical significance was alpha $=0.05$. The η^2 (eta^2) coefficient was chosen to calculate Proprio with reference values: $\eta^2 =$ 0.01 indicates a small effect. $\eta^2 = 0.06$ indicates a medium effect. $\eta^2 = 0.14$ indicates a large effect. The Statistica 14 by TIBCO Software was used to perform the statistical analysis.

A priory sample size was calculated using the G*Power software. With the expected effect size (f $=0.25$ according to Cohen), alpha $=0.05$; power of the test (1-beta $=0.90$), number of groups 3 (resistance training, proprioceptive training, endurance training), with 3 repeated measures (pre-intervention, post-intervention, post-detraining), the total sample size was 36.

We carried out the linear mixed model (Bates et al., 2015; Kuznetsova, 2017) by the software version R 3.6.3. (R Core Team, 2021). The linear mixed model (LMM) monitors the improvement of anterior–posterior CoP sway length (A-P CoP length). A-P CoP length when having eyes closed was observed to be the most reliable parameter of postural stability. The LMM was selected due to its ability to account for individual variability and include random effects, ensuring a more flexible and robust analysis. A linear model with fixed effects was used for modeling. The general shape of the model was:

$$A{-}P\ CoP \sim (1|\mathrm{id}) + \text{knee extensors strength}^{*}\text{group} + \text{HQ}^{*}\text{group} + A{-}P\ CoP\_pre{-}intervention$$

For the categorical variable group, resistance training was taken as the reference group.

Random effects:

- (1 | id) – Two outcome measures were included in the model for each person. One that was done right after the intervention ended and the other two weeks later. This random effect captures the possible different behavior of people in these two weeks (e.g., some voluntarily continued the exercise and may have improved, some stopped and may have started to slowly deteriorate). Monitoring of this behavior was no longer part of the study, so it is a random effect.

- The balance value from the A-P CoP pre-intervention measurement and the values from the two output measurements (post-intervention, and post-detraining) enter the model.

To assess multicollinearity, we used the generalized variance inflation factor (GVIF), ensuring that all predictors met the threshold GVIF^(1/(2*Df)) < sqrt [10]. This criterion helps prevent excessive collinearity, maintaining the stability of the estimates and ensuring the interpretability of the model coefficients.

We excluded missing observations to avoid introducing noise, accepting the reduced dataset size as a trade-off. Unlike traditional methods such as ANOVA, which require listwise deletion, the LMM allows for the inclusion of incomplete cases without biasing estimates. Therefore, missing observations were not excluded in the LMM, ensuring the robustness of the analysis.

Large Language Model (LLM) utilization

We utilized ChatGPT, an LLM developed by OpenAI, to support literature synthesis. ChatGPT employs transformer-based deep learning and is trained on extensive datasets to generate human-like responses. This model assisted with summaries, clarifications, and context-based content generation for complex research topics.

To ensure transparency and reproducibility, we prompted ChatGPT, version 4, accessed in January 2024, with queries tailored to our research objectives. Outputs were reviewed for accuracy and verified against primary sources. While the LLM contributed to preliminary content generation, the authors conducted final interpretations and analyses independently.

Results

Strength parameters were presented in Table 3. Knee extensor strength normalized to body mass significantly increased after the intervention in the resistance training group ($p = 0.01$; η^2: large effect). Knee flexors strength normalized to body mass was observed to increase between the first (pre-intervention) and last (post-detraining) testing in resistance training ($p = 0.027$; η^2: large effect) and proprioceptive training ($p = 0.01$; η^2: large effect) groups. No statistically significant change in HQ ratio was observed in any of the training groups. Toe grip strength was observed to be higher after the intervention in the endurance training group ($p = 0.02$; η^2: large effect) and after the detraining in the proprioceptive group ($p = 0.02$; η^2: large effect) compared to pre-intervention testing. Additionally, the effect size analysis showed increased HQ ratio after the intervention in the endurance training group (η^2: large effect).

Linear mixed model

LMM for standardized values from interval < 0.1 > are shown in Table 4. The LMM focuses on improvement in postural stability (decrease in A-P CoP length) incorporating data from pre-intervention, post-intervention, and post-detraining testing. The results show that in the resistance training group, the postural stability improves with increased knee extensors strength normalized to body mass. In the endurance training group, deterioration in postural stability was observed with an increased HQ ratio. Similarly, proprioceptive training was observed to slightly decrease the postural stability performance with increased knee extensor strength normalized to body mass.

If we take a hypothetical participant of the study (Table 5) with HQ ratio of 0,6, which remained stable during the study period, and a value for A-P CoP length before the intervention of 550 mm, Table 5 shows how the model predicts a change in A-P CoP length, and knee extensors strength normalized to body mass after the intervention for each type of intervention (Fig. 2). For the resistance group (group 1) the A-P CoP length parameter improves with increasing extensor strength. In the other groups, it does not appear that strength has a positive effect on A-P CoP length. In the endurance group (group 3) a negative effect of knee extensor strength on A-P CoP length was observed.

Discussion

Our study aimed to evaluate the impact of a 12-week exercise resistance, proprioceptive, and endurance training interventions on lower limb strength parameters of the knee joint and toe grip, and their relationship to postural stability in older adults. Following this, a 2-week detraining period was assessed to determine the sustainability of these effects. The LMM enabled a comprehensive analysis across various phases of the intervention, including the post-detraining period. This model, considering both fixed effects like the specific interventions and random effects such as individual variability [37], facilitated a detailed examination of how these training modalities influence muscular strength and postural stability over time. The analysis revealed that in the resistance training group, postural stability improved alongside increases in knee extensors strength normalized to body mass. This suggests that resistance training significantly enhances both the muscular strength and the ability to maintain balance, crucial for reducing fall risks among older adults. On

Table 3 Strength parameters at pre-intervention, post-intervention and post-detraining testing for resistance training, proprioceptive training, and endurance training group

			Resistance training			Proprioceptive training			Endurance training		
			Pre-intervention	**Post-intervention**	**Post-detraining**	**Pre-intervention**	**Post-intervention**	**Post-detraining**	**Pre-intervention**	**Post-intervention**	**Post-detraining**
Knee extensors strength normalised to body mass	Left foot	Mean	1.25	1.37	1.37	1.36	1.38	1.25	1.35	1.34	1.29
		SD	0.40	0.48	0.51	0.37	0.32	0.32	0.43	0.51	0.47
		p value	0.007	(η^2=0.34)	AB	0.295	(η^2=0.09)		0.599	(η^2=0.06)	
	Right foot	Mean	1.30	1.45	1.36	1.41	1.46	1.47	1.24	1.23	1.21
		SD	0.42	0.56	0.48	0.37	0.34	0.28	0.40	0.42	0.36
		p value	0.004	(η^2=0.37)	A	0.498	(η^2=0.05)			(η^2=0.02)	
Knee flexors strength normalised to body mass	Left foot	Mean	0.62	0.68	0.68	0.74	0.76	0.74	0.71	0.76	0.71
		SD	0.24	0.30	0.27	0.25	0.23	0.21	0.23	0.28	0.23
		p value	0.027	(η^2=0.26)	AB	0.825	(η^2=0.01)		0.141	(η^2=0.20)	
	Right foot	Mean	0.65	0.72	0.72	0.74	0.79	0.82	0.70	0.76	0.71
		SD	0.24	0.34	0.33	0.21	0.20	0.21	0.20	0.22	0.18
		p value	0.162	(η^2=0.14)		*p*=0.006	(η^2=0.32)	B	0.165	(η^2=0.16)	
HQ ratio	Left foot	Mean	0.49	0.48	0.49	0.55	0.55	0.63	0.53	0.59	0.56
		SD	0.09	0.12	0.08	0.11	0.09	0.32	0.10	0.16	0.07
		p value	0.929	(η^2=0.01)		0.409	(η^2=0.07)		0.148	(η^2=0.19)	
	Right foot	Mean	0.51	0.47	0.51	0.53	0.54	0.55	0.64	0.68	0.63
		SD	0.11	0.1	0.12	0.12	0.07	0.10	0.33	0.28	0.23
		p value	0.533	(η^2=0.05)		0.626	(η^2=0.04)		0.302	(η^2=0.11)	
Toe grip strength normalised to body mass	Left foot	Mean	0.21	0.21	0.21	0.19	0.20	0.20	0.21	0.26	0.23
		SD	0.06	0.06	0.06	0.08	0.08	0.07	0.08	0.09	0.08
		p value	0.715	(η^2=0.03)		0.484	(η^2=0.05)		0.019	(η^2=0.36)	A
	Right foot	Mean	0.19	0.20	0.20	0.20	0.22	0.22	0.22	0.24	0.24
		SD	0.04	0.07	0.08	0.08	0.08	0.09	0.08	0.09	0.08

[A] statistically significant difference between pre and post measurement

[B] statistically significant difference between pre and detraining measurement

[C] statistically significant difference between post and detraining measurement

Table 4 LMM results incorporating data from resistance, proprioceptive and endurance trainings

	Estimate	Std. Error	*p* value	95% confidence int	
(Intercept)	0.17	0.097	0.098	−0.005	0.340
Knee ext	−0.18	0.12	0.156	−0.381	0.038
Proprioceptive	−0.20	0.12	0.104	−0.418	0.008
Endurance	−0.30	0.14	0.039	−0.546	−0.056
HQ	−0.12	0.21	0.563	−0.529	0.250
A-P CoP length	0.72	0.10	< 0.0001	0.549	0.886
Knee ext: Proprioceptive	0.27	0.20	0.195	−0.092	0.613
Knee ext: Endurance	0.41	0.21	0.061	0.052	0.799
Proprioceptive: HQ	0.12	0.26	0.630	−0.326	0.625
Endurance: HQ	0.42	0.26	0.110	−0.054	0.887

Overall model significance

Significance of fixed effects: $p = 0.002$, Significance of random effects: $p = 0.001$

Conditional R^2: 0.866, Marginal R^2: 0.672

Knee ext—Knee extensor strength normalized to body mass

Table 5 A model predicting a change in A-P CoP length and knee extensors strength normalized to body mass after the analysed interventions

	A-P CoP length	Knee ext
Resistance training	*573*	0.8
	477	1.6
	381	2.4
Proprioceptive training	*410*	0.8
	460	1.6
	511	2.4
Endurance training	*473*	0.8
	601	1.6
	729	2.4

the other hand, the inverse effect of muscle strength on postural stability was observed in the proprioceptive and endurance training groups.

In the resistance training group, the postural stability improved with increased knee extensors strength normalized to body mass. In accordance, previous studies have shown that resistance training can improve postural stability through increased knee extensor strength [38–40] The improvement in postural stability observed in the resistance training group with increased knee extensors strength normalized to body mass could be attributed to several factors. Resistance training is known to enhance muscular strength and control. By targeting the knee extensors, which include muscles like the quadriceps femoris muscle, resistance training can improve the ability of these muscles to generate force and provide stability during various movements [22, 41, 42]. As the knee extensors play a crucial role in stabilizing the knee joint, strengthening these muscles through resistance training can contribute to better joint stability, reducing the risk of instability or wobbling during weight-bearing activities [43–45]. Resistance training also induces neuromuscular adaptations, including improved coordination and motor control. These adaptations can enhance the body's ability to maintain postural stability by optimizing the recruitment and firing patterns of muscles involved in maintaining balance [42, 46–48]. Resistance training was observed to enhance proprioception, the body's ability to sense its position in space. Increased knee extensor strength may lead to improved proprioception around the knee joint, enhancing postural control and stability [41, 49]. Participants in the resistance training group may have gained increased confidence in their ability to control their movements and maintain stability. This psychological aspect can contribute to better postural control as described previously [50].

Balance and proprioceptive training interventions were reported to decrease the fear of falls, improve the postural stability and gait [35, 51, 52] Although the proprioceptive or balance training interventions are not specifically designed to improve muscle strength, it can be their additional benefit [52]. Therefore, no association between the increasing knee extensors strength on postural stability improvement in the LMM for proprioceptive group in this study was expected. Still, predictive model of previous study [52] shows that improvement in knee extensors strength can lead to improvements in dynamic balance. This study also reported improvements in isometric strength of both knee flexors and extensors after a balance training program in older people. Similarly, in this study, a statistically significant increase in knee flexors strength was observed in the proprioceptive training group. However, postural stability is a multifactorial construct influenced by sensory integration, cognitive function, and muscular strength [14]. It is possible that without concurrent improvements in these domains, proprioceptive training alone may not produce significant gains. Future research should explore these factors and consider combining proprioceptive training with complementary approaches for greater efficacy.

In the endurance training group, increasing knee extensors strength was associated with a decline in postural stability. The adverse effect suggests a complex relationship between strength improvements and postural control. The observation that increased knee extensor strength during endurance training may correlate with a decline in postural stability has been

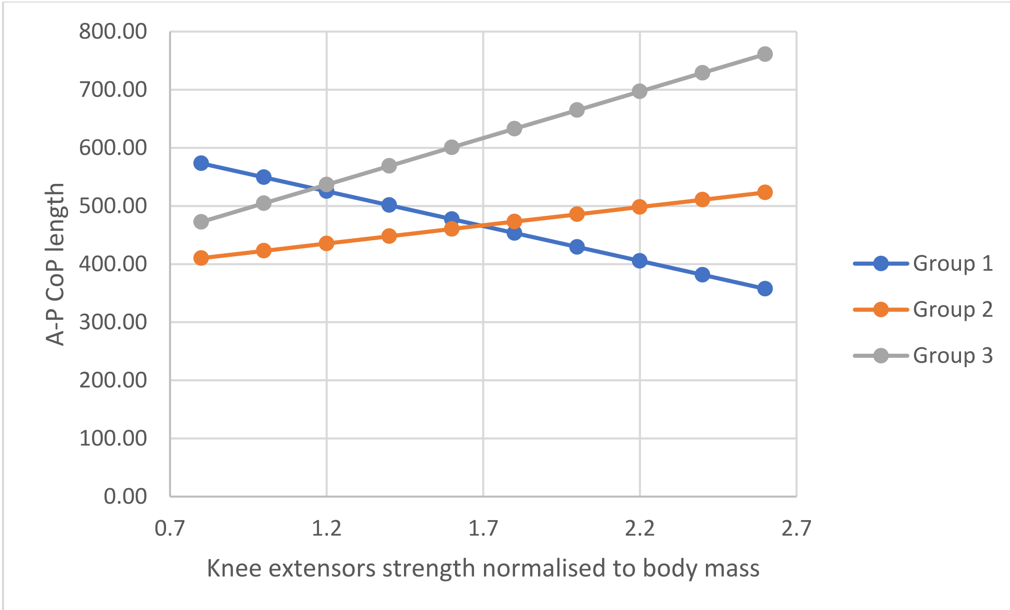

Fig. 2 Change in postural stability with knee extensors strength normalised to body mass. Group 1: resistance training; Group 2: proprioceptive training; Group 3: endurance training

observed previously by several studies examining the relationships between muscle strength, balance, and functional outcomes. Specifically, Nocera et al. [53] highlighted that dynamic postural stability abnormalities might be partially explained by knee extensor function. They noted that as knee extensor strength increases, the capacity to control balance and stability during locomotion can be compromised, particularly during single-limb support phases. This underscores the complexity of strength and stability interactions, suggesting that simply increasing strength does not automatically yield better balance outcomes. This discrepancy may be influenced by the distinct neuromuscular adaptations induced by walking training compared to resistance training. Previous systematic review by Bullo on the effect of Nordic walking exercise in the elderly shows benefits of this exercise on muscle strength of upper and lower limbs, body composition, walking speed and dynamic balance. However, similar to the results of this study, their results showed a negative effect on static balance [54]. The connection between muscle strength and postural stability is intricate, with factors such as muscle typology, muscle function, and age influencing postural performance. Research has demonstrated that muscle strength below a certain threshold can lead to changes in postural performance, emphasizing the significance of adequate muscle strength in maintaining postural stability, especially in older adults [55]. Still, as Nordic walking exercise improves self-selected walking speed, gait variability and locomotor rehabilitation index in older adults it is a recommended form of exercise for this population [56].

Detraining showed varied effects across the different training modalities. Resistance training participants largely retained their strength gains, indicating the more permanent impact of this training type. In contrast, proprioceptive training participants saw some reductions in improvements, particularly in postural stability. Endurance training participants seemed to lose some benefits in postural stability, suggesting that either continuous training or a combination with strength training may be necessary to maintain gains from proprioceptive and endurance training. However, none of these changes reached a statistical significance. All things considered, resistance training turned out to be the most effective strategy for post-detraining strength development and retention.

This study highlights the long-term benefits of resistance training, showing its effectiveness in improving and retaining strength and stability even after a short detraining period compared to endurance or proprioceptive training. The findings also emphasize the need for individualized training programs, ensuring exercise selection aligns with the specific needs of older adults to maximize function and reduce fall risk.

There are several limitations of this study. A small sample size can limit the generalizability of the study findings to the broader population. Additionally, potential sources of bias, including variations in participant motivation and uncontrolled lifestyle factors during the detraining period, may have affected the study outcomes. These aspects should be considered when interpreting and generalizing the current findings.

Understanding how different training modalities influence neuromuscular adaptations and postural control is essential for developing effective interventions to improve balance and decrease fall risk, particularly in populations where maintaining postural stability is crucial for overall well-being. Future research should explore relationships between fall risk, balance, and lower limb strength across exercise types in older adults analyzing also their sensory integration, cognitive function, muscle typology and age as cofactors.

Conclusion

This study provides valuable insights into how different training interventions affect the relationship between muscle strength and postural stability. While in the resistance group, the postural stability improved with increased knee extensors strength, this trend is not evident in other intervention groups. In the endurance group, a negative impact of knee extensor strength on A-P CoP length was observed. These insights could have implications for designing targeted interventions for individuals with specific goals related to fall prevention.

The detraining period also revealed a gradual loss in the training gains. In older adults, the interruptions in training are common, e.g., health complication, family commitments or reduced motivation to maintain regular trainings. Therefore, it is necessary to pay significant attention to the detraining part and its influence on the variables related to the risk of falls.

Based on the findings of this study, several recommendations can be proposed for exercise programs designed for older adults. The findings suggest that resistance training should be part of the exercise programs for older adults, as it enhances postural stability through improved knee extensor strength in addition to increasing overall muscle strength. While endurance training alone did not demonstrate positive effects on static balance in this study, its well-established benefits for cardiovascular health should not be overlooked. Therefore, endurance activities such as walking should ideally be complemented by resistance training in older populations. Additionally, considering the gradual loss of training gains observed during detraining periods, exercise programs targeting older adults should include strategies to promote consistent long-term engagement.

Clinical trial number
Not applicable.

Authors' contributions
Lenka Svobodová - design of the work, wrote the main manuscript text, interpretation of data. Martin Sebera - acquisition data, prepared figures, interpretation of data, contributing author. Tomáš Vodička - acquisition data, interpretation of data. Aneta Svobodová - design of the work, wrote the main manuscript text, interpretation of data. Andrea Horáková - acquisition data. Nikola Stračárová - acquisition data. Šarlota Svobodová - prepared figures, interpretation of data. Veronika Eclerová - data analysis, prepared figures, interpretation of data. Tomáš Vespalec - acquisition data. Mario Kasović - interpretation of data, supervising scientist. Ana Carolina Paludo - interpretation of data, contributing author. Julie Bienertova-Vasku - design of the work, supervising scientist. Marta Gimunová - design of the work, wrote the main manuscript text, interpretation of data. Each author has approved the submitted version (and any substantially modified version that involves the author's contribution to the study) AND to have agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

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Data availability
The datasets used and analysed during the current study are available from the corresponding author on reasonable request (svobodova@fsps.muni.cz).

Declarations

Ethics approval and consent to participate
All participants had given written informed consent before entering the study. The procedures performed in this study were anonymous and according to the Declaration of Helsinki, also approved by the Ethics Committee of the Faculty of Sport Studies of Masaryk University, Brno, Czech Republic (EKV-2018-088-R1).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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